Autonomy Levels for Unmanned Systems (ALFUS) Framework: Safety and Application Issues

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Abstract--The Autonomy Levels for Unmanned Systems (ALFUS) framework is generic and applicable to multiple unmanned system (UMS) domains. The key component of the Framework is metrics along the three established axes or aspects. This paper attempts to examine how the metrics might be applied to selected domains that include homeland security, manufacturing, and defense. In particular, the paper attempts to lay out how the critical UMS concerns, including requirements specification, performance measures, safety, and risks might be established from the Framework.

Key words: *autonomy, contextual autonomous capability (CAC), environment, human independence (HI), human robot interaction (HRI), metrics, mission, task, unmanned system (UMS)*

I. INTRODUCTION

The ALFUS Ad Hoc Working Group has been developing the ALFUS Framework aiming at providing standard terms, definitions, metrics, and tools to facilitate UMS lifecycle practices. Participants from various Government organizations and their contractors, including U.S. Departments of Commerce, Defense, Energy, and Transportation and from industry have been volunteering their efforts. The current results include a terms and definitions document [1], which has begun to be adopted by or referenced in various documents [2]. The Framework document is expected to be published soon.

ALFUS is an ongoing effort. As such, this paper highlights some key accomplishments of ALFUS, discusses current issues, as well as points out future directions.

II. FRAMEWORK

ALFUS is highlighted with a three-aspect model, as shown in Figure 1. The aspects of mission complexity (MC), environmental complexity (EC), and human independence (HI) characterize the autonomy of UMSs. The objective for a UMS autonomous operation is to achieve the missions as assigned by its human operator(s) through the designed human-robot interface (HRI) or assigned by another system that the UMS interacts with. Each of the aspects is further elaborated with a set of metrics, as described in the earlier papers, including [3, 4, 5].

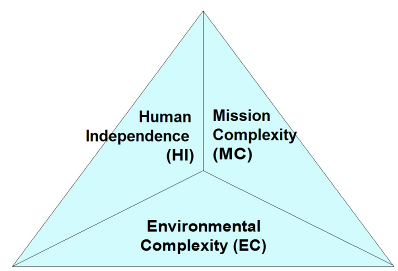

Figure 1: The Three Aspects for ALFUS

A Potential Benefits

Autonomy offers many benefits to human life. The ALFUS framework helps characterizing the autonomy. This characterization process would, in turn, help the design and evaluation of the UMS.

(1) *Enhance safety:* Human safety is the utmost concern in the modern society. However, there are tasks not suited for humans, particularly, those that must be performed in environments that may be

- dangerous—where heavy machinery may be running, a building may be collapsing, or chemical, biological, radioactive, nuclear, and explosive material might exist
- extreme—where it may be too hot, too cold, or too tight
- hostile—where enemy may be firing.

UMSs are suited for these tasks. The ALFUS Framework employs sets of definitions to facilitate communication of the issues and sets of metrics to facilitate the analysis of the issues. For example, in a dangerous environment, certain types of HRI may be needed at certain portions of the mission. The difficulty of the task may not exceed certain levels. These are just some examples for ALFUS application.

(2) *Enhance outcome:* By enhancing outcome, we mean achieving:

- mission/task/order goals
- accuracy and repeatability, in time and space
- savings in time, space, and material

For example, it has been well recognized that those tasks that are repetitive and boring to humans and those beyond human physical abilities could be easily achieved by UMSs. Also, appropriately equipped UMSs enhance the outcome. A UMS with high sensing and perception capability has a better chance of achieving a task requiring high precision.

We attempt to explore applying ALFUS from these perspectives.

III. KEY CONCEPTS IN ALFUS

A key definition in ALFUS is **Autonomy**:

> *"A UMS's own ability of integrated sensing, perceiving, analyzing, communicating, planning, decision-making, and acting, to achieve its goals as assigned by its human operator(s) through designed human-robot interface (HRI)"*

The autonomy is based on the UMS's internal capability of performing all the identified autonomy enabling functions in an integrated manner. This integrated function set forms a complete control cycle. The autonomy is further elaborated into the second key concept in ALFUS, which is called **Contextual Autonomous Capability (CAC)**:

> *"An unmanned system's contextual autonomous capability is characterized by the missions that the system is capable of performing, the environments within which the missions are performed, and human independence that can be allowed in the performance of the missions.*
>
> *Each of the aspects, or axes, namely, mission complexity, environmental complexity, and human independence is further attributed with a set of metrics to facilitate the specification, analysis, evaluation, and measurement of the contextual autonomous capability of particular UMSs"*

This CAC model facilitates the characterization of UMSs from the perspectives of requirements, capability, and levels of difficulty, complexity, or sophistication. The model also provides ways to characterize UMS's autonomous operating modes. The three axes can also be applied independently to assess the levels of mission complexity, environmental complexity, and autonomy for a UMS.

The HI axis is also referred to as the axis for level of autonomy (LOA) [6].

As defined, the CAC model encompasses multiple layers of abstraction. The following are the two essential layers:

- The Metric Model for ALFUS: UMS is characterized with defined sets of metric, including the percentage of a mission that is planned and executed by the UMS onboard processors, the levels of task decomposition, the solution ratio in the physical environment, etc.
- The Executive Model for ALFUS: a UMS is characterized with the three aspects or axes, namely, MC, EC, and HI. These axes are summaries of the individual metrics. Particularly, the weighted averages of metric scores form the axis scores. The HI scores correspond to levels of autonomy, similarly for the levels of MC and EC.

Additional layers of abstraction are allowed. For example, the human interaction time metric along the HI axis might be further decomposed to actuation time, monitoring time, sensory data acquisition time, etc. Earlier concepts even involve another, even higher layer, single CAC score that is a weighted average of the three axis scores. The CAC index is a combination of the metric scores of the three axes and the result can come from many combinations of the three axes. Figure 2 provides an illustration. However, participants are feeling that this might be an oversimplified index. Further investigation of this issue is planned.

The higher layers facilitate requirements specification and communication purposes, whereas the lower levels facilitate implementation and testing and evaluation.

In the research community, the term autonomy level may be used in different contexts. Bruemmer, D.J., et al., in [7], uses the term dynamic autonomy. Barynov and Hexmoor used terms including preference autonomy, choice autonomy, and decision autonomy [8]. In practices, autonomy levels are often used to indicate only the degrees of human independence. They are all consistent with and can be facilitated by the ALFUS CAC model.

The CAC index, including the autonomy level may be used in a nominal sense while the specific level values are dynamic or are adjusting, to the extent of the system design, along the course of mission execution depending on the changes of the environmental and operating conditions.

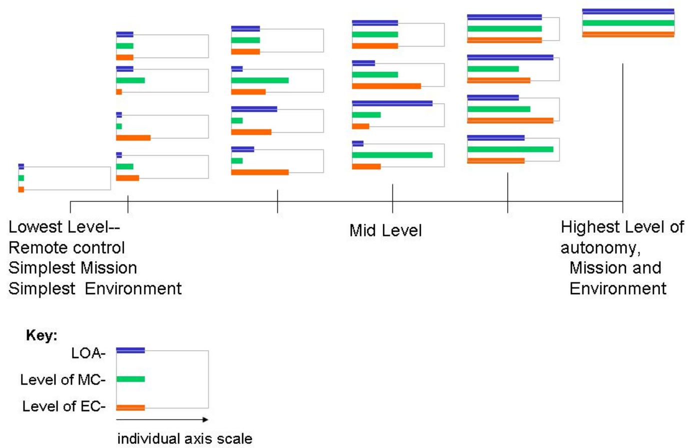

Figure 2: Illustrative Combinations of CAC

IV. ALFUS MODELS FOR UMS SAFETY, RISK AND MISSION SUCCESS

We postulate the following new, key concepts for the purpose of expanding the applicability of ALFUS for UMS.

$$(L(CACR - L(CAC)) \propto L(risk)$$

Where
CACR: CAC Requirements
L: level;
$\propto$ *: proportional to or positively corresponds to*

Note that,

L(risk) <=0

indicates minimal or no risk.

This leads to the following:

$$L(safety) \propto (1 - |L(risk)|)$$

where:

$|\;|$*: normalization*

These, themselves, lead to the following observations:

Level of safety may be contributed by the following factors:

a. insufficient capability in any of the root autonomous capabilities [9]
b. insufficient scores in any of the metrics/axes.

In addition, safety may be considered as a subset of complexity, either mission or environmental.

V. SIMULATION TO FACILITATE AND EVALUATE THE BENEFITS OF AUTONOMY

It is well understood that the application of simulation can save UMS development costs. We investigated how ALFUS could facilitate the UMS simulation.

A Non-Physical Entities

To explore the benefits of UMS simulation, we need to define a set of new ALFUS terms and concepts. Although ALFUS stresses physical UMSs to distinguish itself from the general information technology (IT) world, there are situations when ALFUS is applied to non-physical entities, such as the following:

- Logical UMS (LUMS) are those inherently non-physical entities that interact with UMSs, such as a computer control and management software system like a flexible manufacturing system when it is treated as an independent entity. In a hierarchical control system, a high level control node that coordinates low-levels UMSs may be a LUMS.

- Virtual UMS (VUMS) or Soft UMS (SUMS) refers to UMSs in simulation.

LUMS, VUMS, and SMUS interact with UMSs using established communication channels.

B ALFUS to Facilitate Simulation

A UMS must be specified before development, so does a UMS simulator. There might be two approaches to the development of the simulator, one that is geared toward the specific UMS, and the other toward a generic simulation environment.

For a specific simulator, the ALFUS-based UMS specification is used as design criteria for the simulator. The VUMS should be developed to be able to perform at the level of CAC as the to-be-developed UMS.

In a generic UMS simulation environment, the simulated operating environment might be adjusted, per the design, to the desired difficulty level. For example, the friction of the roads, the slopes of the hills, the density of the traffic, etc., could all be designed as adjustable. The autonomous capabilities of the simulated UMSs can be measured and characterized. These are all benefits facilitated by ALFUS.

The mission could be scripted to the desired level of complexity, as well. Attributes such as the number of VUMSs in a team and the commanding structure, the sensory capabilities, the accuracy of the goals, etc., could be designed as adjustable to reflect the desired level of MC.

Similarly, an ALFUS enabling HRI in a simulator could be designed such that the levels of human interaction time could be adjusted, the types of interactions that the VUMS could initiate could be pre-set, the HRI displays could be adjusted to simulate different levels of stress that might be caused, etc.

VI. APPLYING ALFUS TO MANUFACTURING DOMAINS

A Rationale

Automation is a key to manufacturing efficiency and safety. The challenge is that a manufacturing process could be very complex and dynamic. It could involve operators in a semi-automated facility. It receives work orders for different products and different quantities. It may need to generate various kinds of reports that contain different kinds of information for different purposes such as production control, quality control, or maintenance analysis. The process may also need to adjust its schedules to accommodate storage or shipping constraints. Therefore, a framework for performance measure and capability characterization like ALFUS should be beneficial. The following lists some features that ALFUS could apply:

a. A flexible manufacturing system (FMS), in its entirety, could be considered a UMS. If required, the highest level system software could be considered a LUMS.
b. Equivalent missions/tasks include production orders and inspection orders at a high level, machine a part and inspect a part at a middle level, or drill a hole of X diameter and or inspect the hole at a low level. Correspondingly, the manufacturing system capability could be characterized as number of parts per day.
c. Autonomous capabilities could help the many factors that a manufacturing process may encounter, such as raw material composition/sizes/weights, equipment breakdown, etc. The variation in the raw material could cause adjustments for the equipment, including its settings, workload, and process flow. It should be beneficial that this could be done in a human-machine coordinated way.
d. It is desirable that a manufacturing process's performance be measured. ALFUS might serve this purpose.
e. The EC needs to be characterized for such conditions as a new operator could inadvertently interfere in a work volume, a part might fall off a UMS carrying the lot along the route, or a machine breaks down. In other words, a manufacturing environment could be highly unstructured.
f. The low level machining instructions correspond to the low level skills as identified in the military UMS domain. Skills have different levels of difficulty, so are the machining instructions. For example, for inspecting holes, tolerances make differences in terms of difficulty.

B Toward ALFUS Measures and Indices

Autonomous capability related measures, derived from ALFUS, could help characterizing a manufacturing process in the following possible ways:

a. Highly autonomous manufacturing UMS might correspond to higher initial equipment cost but lower overall lifecycle cost as well as higher capability for complex "missions," i.e., products.

$$\left|\textit{initial cost}\right| \propto L(CAC))$$

$$\left|\textit{lifecycle cost}\right| \propto (1 - L(CAC))$$

b. Lower complexity products might mean that they are suitable for mass production on low CAC manufacturing UMSs.

C Examine a Safety Model for a Industrial Process

The following is a multiple layers safety model for a manufacturing process plant, listed from narrow to broad scopes or from the low to high levels, i.e., item #a is the lowest level and item #h the highest. The higher level safety design activates when the low level design fails [10]:

a. to design the equipment, turning, milling, drilling, forging, die-casting, rolling, etc., and process plant to be inherently safe
b. process control to be designed with safety functions
c. procedure for and activation of alarms and operator intervention
d. safety shut down and interlock of affected entities
e. response mechanisms for fire and gas
f. containment system for the hazard
g. plant emergency response evacuation system
h. community emergency response evacuation system.

Each step contains an independent safety design, yet they are integrated to produce a coordinated safety operation.

We observe that system configuration is expanded and system complexity increases from the lower to higher levels. As a result,

a. Safety related missions or tasks become more complex.
b. The operating environments become broader and involve more entities. They may tend to be more dynamic and unstructured.
c. Higher levels of CAC provides for higher capability for safety.

VII. ADDITIONAL DOMAINS

A. Defense

UMSs are well suited for military types of operations. UMSs can replace soldiers in harm's way and can get themselves in extreme operational and environmental conditions. War fighting, surveillance, medical assistance in the field, logistic support, etc., are just a few of the fruitful areas for UMS deployment. These are also rich issues warranting the application of ALFUS.

B. Search and Rescue (SAR)

One of the major concerns in SAR would be the environment. Would it be accessible? Would it be safe for responders to approach? How is an environment or an environmental condition be described and conveyed to the decision maker so that the following issues, among additional, others, can be revolved: an appropriately composed and equipped Emergency Response Team [2] be dispatched, at a certain Point of Arrival, whether and what kind of Incident Support Team might be needed, and, possibly, under the command of a certain Federal Coordinating Officer.

EC levels might be used to identify particular environments used for robotic certification.

Efforts have also begun at NIST to establish the performance metrics for SAR robots by developing test arenas with various, adjustable levels of difficulty [11, 12].

C. Border Security

Variety in terrain and lengths in distance are among the challenges of securing the National borders. For the portions of the border that is difficult to traverse, ALFUS could be applied to characterize the levels of complexity, which could facilitate deploying UMSs with appropriate CACs. For the busy crossing ports, UMSs could help the safety related tasks such as baggage checking and identity verification. ALFUS could help characterizing the task complexity specifying HRI requirements.

D. Bomb Disposal

The ultimate concern for bomb disposal would be safety of human. Therefore, this is the type of task for UMS. ALFUS could help analyze the complexity of such an operation. The results could help optimize human assistance, including a safe operating condition and environment for the involved operator.

E. Standard Mission/Task Ratings

Skill ratings for human tasks are used [13, 14, 15]. It would be interesting to explore similar ratings for UMS. For a particular domain, a collection of tasks or a collection of typical scenarios that involves the combination of task, environment, and HRI can be rated for CAC. The information would be maintained in a database. When a situation arises that calls for the deployment of a UMS, the situation could be analyzed and the matching tasks or scenarios could be identified. The information could be used to efficiently deploy a capable UMS to handle the situation.

VIII. SUMMARY

Key concepts for the ALFUS Framework are introduced, with particular focus on the safety issue. A selected set of domains are analyzed for the applicability of ALFUS, including manufacturing, military, and homeland security. We discovered that ALFUS CAC should be helpful for indicating a robot's ability to conduct certain missions. We also discovered that each application domain may be unique that warrants expansion of the existent metric sets in ALFUS. Safety concerns also warrants expansion of the existent metric sets.

ACKNOWLEDGEMENT

ALFUS participants contribute to the Framework contents through workshop participation. Funding sources for this effort, throughout various stages of the Framework development efforts, include Department of Homeland Security, Science and Technology Directorate, Army Research Laboratory, and NIST.

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